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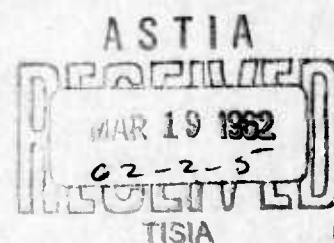
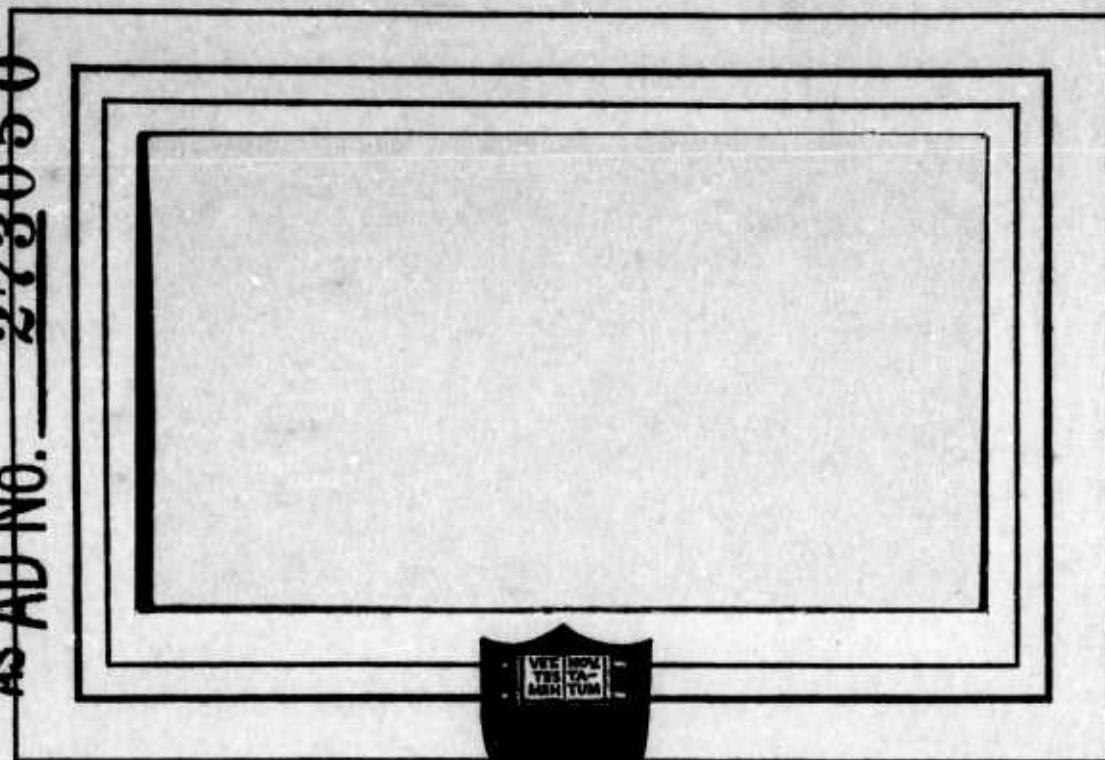
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Fort Eustis, Virginia

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Final Report -

A Summary of the

Princeton University - U. S. Army ALART Program

Report No. 566

January, 1962

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## FOREWORD

The Princeton University - U. S. Army ALART program, Contract No. DA-177-TC-524, has spanned the time period January 1, 1959 to December 31, 1961 and has been exclusively devoted to research in several areas of low speed flight. The end product of this work is a number of technical reports, each of which is summarized in a later section of this paper. It is felt that this is the most meaningful method of presenting the accomplishments of the over-all program.

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## I. Introduction

Prior to January 1959, several research projects, largely funded by the U. S. Army, at Princeton University were effectively brought together under an all encompassing Army Low-Speed Aeronautical Research Task (ALART). These projects have formed the backbone of ALART; however, during the past year considerable diversification into new areas of research has developed both at Princeton and elsewhere by means of sub-contracts. The total effort over the past three years has produced forty technical reports, thirty-eight of which are Princeton Aeronautical Reports, in addition to several papers.

The primary programs, very generally stated, were and are:

1. Research dealing with the hovering, transition, and slow forward flight dynamic characteristics of the several types of VTOL craft. This work is both theoretical and experimental - the experimental portion carried out in the Forward Flight Facility (Long Track).
2. A program dealing with the dynamic stability characteristics of full scale helicopters. Again this work is both theoretical and experimental - the experimental portion being accomplished by means of a variable stability HUP-1 helicopter. The results are generally not restrictive to the HUP-1 but are broadly applicable.
3. A program investigating the dominant problem areas of Ground Effect Machines has been underway throughout the past three years. This field is so new that most of the work has been exploratory - dealing with stability in hover and forward flight, control, and performance. The work has been analytical, theoretical and experimental. The experimental portion of the research has utilized many models for static testing, wind

tunnel and long track experiments, and several manned machines.

During the past year, while continuing work in the above three fields, new research has been initiated dealing with the helicopter static charge phenomena, adaptive control and stability and a design study for a wind tunnel of unique capabilities to adequately test high downwash angle aircraft.

In addition to this expansion of effort, cooperative programs have been carried out with VERTOL, CONVAIR and the Kellett Company, all of whom have TRECOM contracts in fields relating to ALART work. A cooperative program with DTMB - ONR - TRECOM as well as sub-contracts with both the Kellett Aircraft Company and Curtiss-Wright Aeronautical have been completed.

A more detailed presentation of these programs will be discussed in the next section.

## II. Discussion

Each of the separate ALART programs have been identified as separate phases as listed below:

Phase 1 - Research in the field of Dynamic Flight Characteristics utilizing the Forward Flight Facility (Long Track).

Phase 2 - Research dealing with the problems of Ground Effect Machines.

Phase 3 - Theoretical Research dealing with the fundamental problems of Flying Jeeps and Flying Platforms.

Phase 4 - Research dealing with the handling qualities and dynamic stability of Helicopters and V/STOL type aircraft.

Phase 5 - An analytical program determining the feasibility and



significance of a Flying VTOL Simulator.

Phase 6 - An essentially theoretical program with some experimental correlation looking into the fundamental causes of static electricity build-up in aircraft.

Phase 7 - A study of the feasibility and desirability of a static test facility (special wind tunnel) designed particularly to handle the high downwash angle problem.

Phase 8 - An essentially theoretical study with experimental correlation to determine the applicability of adaptive control and stability to ground effect machines.

Within phases 1, 2 and 4 distinct and separate studies have been made and individually reported upon over the past three years. The approach to research in each of these three major areas of the ALART program follows.

#### ALART - Phase I

A serious problem area in the development of helicopters and VTOL aircraft arises due to the unsatisfactory handling qualities of the basic airframe in hovering and at slow forward speeds. These poor stability and control characteristics, as well as making the aircraft difficult to fly, restrict its utility under adverse weather conditions and in situations requiring precise maneuvering. Real improvements in the dynamic characteristics of these aircraft can result only through experimental research to improve and extend theoretical prediction techniques.

Conventional methods of experimentation, i.e., flight and wind tunnel testing are plagued by numerous difficulties in this speed range.

In flight testing at low speeds, for example, measurement of aero-

dynamic quantities is a significant problem. Wind tunnels present unknowns in testing where the slipstream velocities are at least of the order of the forward speed or greater, when the wall effects become increasingly important. In addition, wind tunnels ordinarily provide only static stability information.

Therefore, it was considered desirable to develop an apparatus uniquely suited to the experimental investigation of the dynamics of aircraft at low speeds. Under ALART I the design and construction of such an apparatus was completed, and numerous experiments were conducted. The most important feature of the facility is that it is possible to measure directly the dynamic response of a VTOL model dynamically similar to the full scale aircraft at any time during the transition from hovering to forward flight.

The apparatus consists of a servo-driven carriage riding on a 750 ft. long track, housed in a 30' square cross section building. Dynamically similar models are flown in unrestrained flight in the plane described by the vertical and the heading of the model. The model can move with respect to the carriage a limited distance ( $\pm 6$  inches horizontally and  $\pm 2$  inches vertically) in this plane without being influenced by the presence of the carriage. This relative motion, the displacement of the model with respect to the carriage, is the driving signal (error signal) for the positioning servomechanisms that determine the motion of the carriage. The performance of the servomechanisms makes the carriage capable of following any reasonable motions of a model. Thus the free motions of the model completely determine the motion of the carriage, and accurate measurements of the motion of the model along the track are made during the

period of time in which the relative displacement between the model and the carriage is less than the above limits. One servomechanism drives the entire carriage in response to the horizontal motions of the model, and another drives the horizontal tapered tube up and down with respect to the carriage to follow altitude changes of the model. It should be noted that this apparatus is entirely distinct from a wind tunnel and provides quantitative data that cannot be obtained in a wind tunnel or for that matter in any other facility in existence.

In summary, the following major items were accomplished by ALART I:

1. The basic apparatus described above was developed from a preliminary design stage to an operational research tool, and models and instrumentation systems suitable for use on such a research tool were successfully constructed and employed.

2. Experiments were conducted which demonstrated that the longitudinal dynamics of a single rotor helicopter model and tilt wing VTOL model measured using this apparatus provide accurate simulation of the dynamic characteristics of their full scale counterparts.

3. Additional experiments were conducted to provide verification of existing theories and to develop new theory where necessary for the prediction of the dynamics of aircraft at low speeds.

4. Theoretical studies on the dynamics of helicopters and VTOL aircraft were also carried out, complementary to the experimental work.

There follows a complete listing and brief resume of reports on research conducted under ALART I in the next section. Each of these reports presents results of work directly concerned with one or more of the four items categorized above. Considered as a whole, this group of reports represents the

aggregate of significant accomplishments under the ALART I program.

#### ALART - Phase II

The ground effect program has, by the very nature of work in a new field, been highly exploratory. Considerable emphasis has been placed upon the determination of basic flows and characteristics of these craft rather than upon the collection of routine design data. The work has been theoretical, analytical and experimental, the latter portion utilizing many wind tunnel, long track and static models, each designed to shed light upon a particular, not well understood, characteristic. This work has been kept upon a realistic plane by the experimentation with several man-carrying GEM's, the most significant of these being the P-GEM. With this craft three separate series of studies have been successfully completed and reported upon in addition to a cooperative TRECOM - Kellett - Princeton dynamic investigation utilizing the machine.

During the past two years of the program approximately two thousand visitors have been received by this project from all parts of the U.S.A. and nine foreign countries. These visitors included technical representatives from virtually all the free world's aircraft industry and some automotive concerns and other companies interested in one or more aspects of transportation. This phase of ALART organized and sponsored the 1959 Princeton - TRECOM Ground Effect Symposium, the proceedings of which are the worlds first collection of significant work in the field.

In addition to these contacts further dissemination of the Princeton - TRECOM GEM results has been made through a number of technical reports (tabulated in a later section) and through the medium of motion picture

films which have been loaned for showing to various U.S.A. and foreign audiences.

Major accomplishments of the Princeton Ground Effect Program have been:

- a) The determination of the two dimensional flow characteristics of a hovering peripheral nozzle.
- b) Full scale flight measurements of controllability, stability and momentum drag of the P-GEM.
- c) Qualitative observations of full scale P-GEM operation over land, snow and water.
- d) The determination of the power required for inherent static stability up to  $h/D$  values of .12 for several base configurations.
- e) Wind tunnel studies of a 1/12 scale model of the P-GEM dealing with lift, drag and pitching moment of the configuration at various heights above the ground.
- f) Smoke studies of both hovering models and the forward flight condition (in three dimensional smoke tunnel).
- g) The study of the effect of planform shape on hovering performance and stability.
- h) A study of the hovering and forward flight characteristics of a cruciform GETOL.
- i) The determination of certain forward flight dynamic characteristics of the P-GEM (Long Track experiments).
- j) A basic analysis of the maneuvering characteristics of peripheral jet ground effect machines.

k) A theoretical study of the effect of forward flight on a two dimensional peripheral jet ground effect machine.

l) A study, both experimental and analytical, of the applicability of sailwings to GEMs.

m) A wind tunnel investigation of the characteristics of an experimental transition GETOL craft.

n) An experimental determination of the performance and internal flow fields of several types of open plenum, two dimensional GEMs.

In addition to the studies tabulated above, each of which has been reported upon (see next section), two sub-contracts have been completed, one with the Curtiss-Wright Company and the other with the Kellett Company. The purpose and accomplishments of these sub-contracts is also described in the next section of this report.

#### ALART - Phase III

This phase was a relatively short term one. It was devoted to the analysis of the inherent static and dynamic stability problems associated with ducted and unducted flying platforms and aerial jeep type aircraft.

The results of these studies are summarized in a later section of this report.

#### ALART - Phase IV

This phase of ALART deals primarily with the study of the dynamic stability, control, and handling qualities of V/STOL aircraft and helicopters. The design and complete mission utility of current and future V/STOL aircraft dictates that considerable information be available or known in the area of stability and control processes.

Recent progress in the V/STOL field has demonstrated the feasibility of numerous different configurations at least from the mechanical and performance standpoint. However, the handling characteristics of V/STOL designs are almost entirely unknown and little information is available on similar methods of predicting acceptable flying characteristics of the various novel designs.

Since the principal interest in the handling qualities of V/STOL vehicles is in the area of transition, a three dimensional, six degree of freedom problem with large and varied accelerations, the investigations become difficult and complex. In fact, the dynamical equations describing the flight mechanics of V/STOL aircraft are highly non-linear with variable coefficients so that mathematical analysis is extremely difficult. There is neither analytical nor empirical frame work for description of their flying qualities, much less quantitative data defining boundaries of acceptability or even safe operation.

While it may be evident that research in this area is essential to rapid progress in the development of operationally suitable machines of this type, the methods and available facilities required to conduct such studies are not fully appreciated. There are varied ideas on problem recognition and problem formulation on investigations in this field that are complex and not well understood even at the most fundamental levels. For example, opinions differ on the use of ground simulator data versus flight data, type of data to obtain, the validity, and how it is to be analyzed. In the past, considerable theoretical and analytical work in this area has been accomplished by Princeton University. In addition, equally important experiments have been conducted using ground based

simulators, analog computers and a variable stability helicopter to obtain actual pilot opinion and flight data. Any investigations conducted in this area must, by their nature, include appropriate utilization of all techniques and facilities if useful and valid information is to be obtained in a reasonable time. For instance, it is certainly questionable to extrapolate broad conclusions on handling qualities criteria obtained from a fixed base ground simulator to "an analogous" flight situation in V/STOL transition where the aircraft is experiencing large, varied accelerations and flight excursions with steep gradients. Acceleration cues can cause significant differences in a specified problem since they may provide the pilot with either favorable or unfavorable sensations depending on the conditions and desired performance expected of him. Also, the extent to which valid conclusions may be drawn in the study of human response characteristics from data obtained by ground simulation on V/STOL transitions is virtually unknown, if in fact possible at all. In this respect, the importance of actual flight experimentation phases to any research in this area cannot be over emphasized. Pilot opinion obtained in closely controlled flight experiments using properly trained pilots has long been accepted as a valid and essential element in the final determination of criteria defining suitable handling qualities of aircraft. In the final analysis, all other methods of study must, on frequent occasions throughout the progression of the entire experiment, yield to actual flight experimentation in order to obtain meaningful conclusions.

During the past three years, the ALART IV research group has conducted research into the area associated with dynamic stability and handling qualities of V/STOL aircraft. Included in the next section are a summary



of all reports written under this phase of the ALART program.

#### ALART - Phase V

This phase was devoted to the analytical study of a flying flight simulator. In concept such a simulator would be required to exhibit all the handling qualities of a VTOL aircraft from hovering through transition to slow cruising flight.

The results of these studies are summarized in a later section of this report.

#### ALART - Phase VI

Phase VI of ALART was devoted to the determination of the feasibility of the use of passive coating methods in reducing the accumulation of charges on an aircraft in flight. A short theoretical study was also pursued on the charging and discharging problems of an aircraft in flight.

#### ALART - Phase VII

This phase of ALART undertook a study of existing V/STOL test facilities. This, of course, centered around wind tunnels applicable to the testing of models with high downwash angles. The study defined the problems associated with model testing of V/STOL craft and generally established acceptable boundary test conditions for a wind tunnel uniquely designed for this type of testing.

#### ALART - Phase VIII

Phase VIII was devoted to the analytical and experimental study of artificial stabilization of GEM's. Because of the relatively high power cost of obtaining inherent aerodynamic stability of these craft it has been

deemed wise to investigate the complexities of an adaptive stability system utilizing feedback methods.

A summary of the program and the resulting reports appear in a later section.

### III. ALART Publications

The end product of a basic research group is the dissemination of its findings by publication as laboratory reports, papers, speeches, films, and verbal presentations to qualified technical visitors. As has already been indicated the various ALART groups have followed, whenever appropriate, all of these methods. An effective recapitulation of the over-all three year effort follows with the listing of each ALART report and a summary statement of the scope of each individual study:

#### ALART - Phase I

1. Bennett, Robert M. and Curtiss, Howard C. Jr., An Experimental Investigation of Helicopter Stability Characteristics Near Hovering Flight Using a Dynamically Similar Model, Princeton Aero. Report No. 517, July 1960.

Experiments were conducted to investigate the near hovering transient response of a single rotor helicopter, in two degrees of longitudinal freedom, and, in particular, to determine the pitch damping and the velocity stability.

It was concluded that the pitch damping could be predicted with good accuracy using conventional formulas, but that there was a significant deficiency in the predicted value of the velocity stability due to the influence of the rotor wake on the fuselage.

2. Curtiss, Howard C. Jr. and Putman, William F., Results of Experimental Correlation of Model and Full Scale Helicopter and VTOL Longitudinal

Dynamics, Princeton Aero. Report No. 543, April 1961.

Experiments were conducted to determine the degree to which the three degree of freedom longitudinal dynamics measured on the facility using two dynamically similar models, simulate the characteristics of their full scale counterparts. Model results were compared with flight test data taken by NASA on the tilt wing VTOL aircraft, and data taken by Princeton on the single rotor helicopter. Excellent agreement was obtained between each model and its full scale counterpart. The agreement on two widely different configurations provides a firm basis for the inference that any model tested on the track will be a good representation of its full scale counterpart.

3. Putman, William F., Results of Experiments on a Tilt-Wing VTOL Aircraft Using the Princeton University Forward Flight Facility, Princeton Aero. Report No. 542, May 1961.

This report presents the results of initial longitudinal static stability and control and partial transition investigations on the Forward Flight Facility. The model employed in these tests was a two rotor tilt-wing VTOL configuration.

Included in this report are discussions of the equipment and testing techniques as well as a development and evaluation of various analytical approaches to the prediction of the static and dynamic characteristics of the wing-rotor system.

Results demonstrate that accurate prediction of the aircraft characteristics requires more fundamental investigations of the wing-rotor system and that the slipstream rotation effect on wing local flow conditions may exert a strong influence on aircraft stability and control.

4. Hargraves, C. R., An Analytical Study of the Longitudinal Dynamics of a Tilt-Wing VTOL, Princeton Aero. Report No. 561, June 1961.

This report is a theoretical investigation of the longitudinal dynamics of a general tilt-wing aircraft. The stability is investigated for various wing-tilt angles from hovering to forward flight. The analysis is presented in such a way that the various component contributions to the stability derivatives can be seen, and the importance of the wing-slipstream forces are shown. Of particular interest is the influence of the wing immersed in the rotor slipstream on the velocity stability derivative,  $M_v$ , at low forward speeds. The large magnitudes of  $M_v$  produced in this manner are extremely detrimental to the longitudinal dynamics of the aircraft in hovering and at low forward speeds.

5. Martinez, Esteban, A New Facility for the Study of Aircraft Dynamics, Princeton Aero. Report No. 532, July 1961.

This report describes in detail the design philosophy behind the Forward Flight Facility and how the apparatus functions. Included are discussions of all major component parts and system operations with particular emphasis on limitations and future potential of the apparatus as determined by its constituent parts.

6. Curtiss, Howard C. Jr., Some Basic Considerations Regarding the Longitudinal Dynamics of Aircraft and Helicopters, Princeton Aero. Report No. 562, July 1961.

This report is a theoretical study pointing out the influence of the important stability derivatives on the transient motion of aircraft and helicopters.

A discussion of the longitudinal motion of an airframe is presented. General relationships between the stability derivatives of the airplane and the single rotor helicopter are considered. It is shown that the

basic character of the longitudinal motion is primarily determined by the angle of attack stability and the velocity stability. The variation in the modes of motion produced by these two stability derivatives is presented.

Consideration of the relationships between the flight variables in the modes of motion is included.

7. Edenborough, H. K., An Analysis of the Effect of the Rotor's Rotational Degree of Freedom Upon Helicopter Longitudinal Stability, Princeton Aero. Report No. 555, September 1961.

This report is a theoretical investigation of the influence of the rotor angular velocity freedom. Within the restrictions of the analytical assumptions it is demonstrated that consideration of this additional degree of freedom will result in some significant effects on the helicopter's longitudinal dynamics, particularly in the short period mode. In general, this refinement will affect a decrease in the period of the short period mode, and an increase in that of the phugoid mode, and a marked decrease in the damping of the short period mode.

It is believed that these results are of sufficient interest to warrant future experimental investigation and confirmation of this phenomenon.

8. Curtiss, Howard C. Jr., Putman, William F., and Koo, Jiro, An Experimental Investigation of Helicopter Stability Characteristics at an Advance Ratio of 0.1 using a Dynamically Similar Model, Princeton Aero. Report No. 575, December 1961.

An experimental investigation of the Dynamics of a Helicopter model at an advance ratio of 0.1 including a comparison with the Full Scale dynamics.

This report presents the results of an experimental investigation of the longitudinal three degree of freedom transient response of a single rotor helicopter in forward flight. The research demonstrates how the

facility can be used to determine the stability derivatives as well as the transient response of a model. Comparison between the predicted and the measured stability derivatives is given. In addition, the comparison between the model and full scale aircraft dynamics is presented in more detail than in the correlation report.

Worthy of particular mention are the gross inaccuracies incurred in attempting to predict the longitudinal force derivative  $Z_u$ , the rate of change of vertical force with forward velocity. This particular deficiency is a result of limitations in the isolated rotor theory at the advance ratio under consideration and demonstrates the strong need of more fundamental investigations in this flight regime.

9. Putman, William F. and Curtiss, Howard C. Jr., An Experimental Investigation of Tilt Wing VTOL Stability Characteristics Near Hovering Flight Using a Dynamically Similar Model, Princeton Aero. Report No. 576, December 1961.

This report discusses results of experiments performed with a tilt wing VTOL model using transient response dynamic and static testing techniques. Comparisons are made of the various experimental techniques as well as with analytical predictions based upon techniques developed in Princeton Reports No.'s 543 and 561. In general, confirmation was obtained of the excessive magnitudes of  $M_v$  predicted in these reports, and of its detrimental effect on the aircraft's longitudinal dynamics. In addition, no marked change in the aircraft's characteristics was affected by replacing the flapping rotor with an identical rigid rotor, and both configurations exhibited small but favorable pitch damping with  $M_0 = - .6$  on the model.

## ALART - Phase II

1. Nixon, W. B., Sweeney, T. E., Some Qualitative Characteristics of a Two Dimensional Peripheral Jet, Princeton Aero. Report No. 484, September 1959.

This report deals exclusively with base pressure distributions of a two-dimensional peripheral jet model in simulated hovering flight. Flow patterns have been deduced from these distributions and have been verified with smoke studies. The standing vortex associated with this type of device is plotted as a function of altitude and angle of inclination, and the relationship between the vortex and static instability is shown for three initial jet angles.

Also included is a brief discussion of the unsteady flow pattern generated at certain altitudes and initial jet angles. This flow is plotted and is shown to deteriorate, apparently, into a Karman street - possibly explaining the critical altitude reported by other investigators.

2. Sweeney, T. E., Some Notes on the Ground Effect Phenomena and The Princeton Program, Princeton Aero. Report No. 493, December, 1959.

This report deals with the state of the art as of the time of its publication. It is purposefully semi-technical in nature, it being intended to answer as broadly as possible the many questions brought to Princeton by an intensely interested general public.

3. Nixon, W. B. and Sweeney, T. E., Preliminary Flight Experiments With the Princeton University Twenty-Foot Ground Effect Machine, Princeton Aero. Report No. 506, January 1960.

This paper deals with measurement of control moments and rates, drawing a comparison with the controllability of a HUP-1 helicopter. Fundamental flow studies are discussed and illustrated by means of diagrams and tuft pictures. Full scale drag measurements are reported and the

problem of momentum drag is discussed and shown to be a function of the flow change over the machine's surface produced by the sink. Full scale lift augmentation ratios as a function of the height parameter are presented and compared with those of a 1/12 scale model. The results of hovering performance studies are reported and compared to Chaplin's simple momentum theory. Over-all handling characteristics are discussed and observations of the machine's performance over rough and smooth surfaces and snow are included.

4. Nixon, W. B., Maneuvering Capability of an Annular Jet Ground Effect Machine, Princeton Aero. Report No. 515, May 1960.

An elementary analysis, employing non-mixing theory, is made of three general methods of control. The possible advantages of redistributing the annular jet strength are investigated. The slanted jet "integrated" system is the most effective within certain restrictions. Separate thrusting and tilting are seen to have some attributes, particularly in practical application. Side force fins are suggested. The pitching moments introduced with the application of control forces are discussed. Yaw control is found to be more effective with the slanted jet. A comparison with other surface vehicles accentuates the maneuvering limitations of a GEM. Operation over land may require much higher hovering capability than is generally conceded on the basis of performance.

5. Wright, D. E., The Effect of Configuration on the Lift Augmentation Ratio of a Two Dimensional Open Plenum Ground Effect Machine, Princeton Aero. Report No. 516, May 1960.

This report deals with the base pressure distributions of a two-dimensional open plenum ground effect machine model in simulated hovering flight. The following design parameters were varied, nozzle area/base area, side depth, mass flow, side inclination, and flow diversion. The



effect of the variation of these parameters on the pressure distribution, hence lift augmentation was investigated. Flow patterns have been deduced from these distributions and from smoke studies.

Also included are a brief theoretical investigation and an investigation into the effect of inclining the model.

6. Davies, H. J., Preliminary Report on the Theoretical Treatment of the Two Dimensional Ground Effect Machine in Forward Motion, Princeton Aero. Report No. 533, January 1961.

An idealized model of a two dimensional ground effect machine in forward motion is treated theoretically. Ideal potential flow is assumed and the Schwartz-Christoffel transformation is used to obtain the flow equations. A symmetrical model about the mid-point is assumed with jets tilted inward.

7. Sweeney, T. E. and Nixon, W. B., Some Notes on the P-GEM, Princeton Aero. Report No. 537, January 1961.

Certain observations are reported in a qualitative manner regarding operational and other flight experiences with the Princeton 20 Ft. Ground Effect Machine. Comments on the fan-inlet problem, stability and stabilizing devices, and operations over land, water and snow are made as a result of many hours of operation of the P-GEM. Tentative conclusions are drawn which largely reflect the authors' opinions as influenced by the observations.

8. Sweeney, T. E., The Effect of Planform on the Static Characteristics of Peripheral Jet Wings, Presented GEM Contractors Symposium, Ft. Meyers, Virginia, October 1960.

This report includes the preliminary findings of a series of experiments which were designed to determine the effect of planform upon hovering performance and static longitudinal and lateral stability of

peripheral jet wings.

Planforms tested included an aspect ratio range of 1 through 4 (rectangular wings), a aspect ratio 4, 30° swept planform and a 60° delta. The ratio nozzle area to base area was held constant for each model. Also presented is a theoretical analysis of the effect of asymmetric nozzle widths upon the hovering center of pressure. This is compared to actual experimental results.

9. Sweeney, T. E., A Disclosure of The Sailwing Concept, May 1961.

This brief report was prepared to fulfill a requirement of the ALART contract to disclose to TRECOM an invention first reduced to practice under the contract. The report describes, in a general manner, sailwings, their possible planforms and one possible application to a ground effect machine.

10. Sweeney, T. E. and Nixon, W. B., Planform Characteristics of Peripheral Jet Wings, Princeton Aero. Report No. 524, September 1961.

The effect of several planforms on the hovering lift augmentation ratio, static longitudinal stability and static lateral stability of peripheral jet wings are considered. The planforms tested were selected to be representative of useful GETOL wings and include rectangular wings of aspect ratio 1 through 4, a 30 degree swept wing and a 60 degree delta wing. The static characteristics of a tapered wing are also included.

The effect of asymmetric leading edge and trailing edge nozzle widths is theoretically predicted and compared to experimental findings.

11. Sweeney, T. E., The Forward Flight Characteristics of a 1/12 Scale Model of a Research GETOL Craft, Princeton Aero. Report No. 577, November 1961.

This report covers a series of wind tunnel experiments looking into the airplane characteristics of a configuration designed to be a reasonably good GEM with optimum transition capability. The model configuration was that of a tailless winged delta. Results presented in Report No. 577 include the lift, drag and pitching moment as a function of angle of attack and h/c ratios including  $h/c = \infty$ .

12. Sweeney, T. E., Exploratory Sailwing Research at Princeton, Princeton Aero. Report No. 578, December 1961.

This report describes the Sailwing structure and presents both qualitative and quantitative findings of experiments with a 12 foot sailwing mounted on a model glider. In addition, the results of three dimensional wind tunnel experiments with a 2 foot sailwing are discussed and compared with the performance of a conventional wing under similar conditions of tunnel tares and Reynolds Number.

Some tentative conclusions are drawn relative to the applicability of the sailwing to GEM's and other craft. Recommendations for future work in this field are also made.

13. Nixon, W. B. and Sweeney, T. E., The Power Required for Inherent GEM Static Stability, Princeton Aero. Report No. 579, December 1961.

The brake horsepower required for the inherent aerodynamic stabilization of the P-GEM for several base compartmentation configurations is discussed in this report. The data are quantitative having been acquired by both full scale experiments with the P-GEM and with a 1/12 scale model of the same machine.

14. Summers, D. and Knowlton, M. P., Stability and Performance Characteristics of a Cruciform GETOL, Princeton Aero. Report No. 580, October 1961.

The cruciform planform was developed to overcome the static instability problems of a GEM and to evaluate the performance of a GETOL with and without wing blowing. This report deals with the lateral and longitudinal stability and the performance of a GETOL vehicle at forward speeds up to 37 fps. or, in terms of the pressure ratio  $q_0/p_0$  from zero to 3.46.

Static stability studies were conducted for both roll and pitch for five different configurations. The different configurations were developed by closing off portions of the peripheral jet around the basic cruciform shape. The model exhibited good lateral and longitudinal stability for most configurations up to an  $h/\text{mac}$  of .96, the highest altitude tested. Generally the stability decreased with an increase in  $h/\text{mac}$ .

Forward flight tests were conducted on the long track facility at Princeton. The model, fixed in pitch, but free to seek its own hover altitude was driven down the track by the servo carriage. Altitude gain at two angles of attack was measured from which a lift coefficient was calculated. Lift coefficients were generally found to decrease with angle of attack at low speeds and increase with angle of attack at the higher speeds.

15. Wojciechowicz, A. and Knowlton, M. P., Model Studies of the Forward Flight Characteristics of the P-GEM, Princeton Aero. Report No. 581, November 1961.

A wind tunnel investigation using a conventional ground board setup has been conducted to determine the forward flight characteristics of a model of the P-GEM both within and without the proximity of the ground. Separate studies were made of the model with wings attached at several locations around its perimeter and also with the addition of a tail. The

results showed that for all configurations, as the ground was approached, increases in lift curve slope and reduction in induced drag resulted in increase of lift-drag ratio. It was also found that the longitudinal static stability could be significantly increased with the addition of properly located wings or a tail.

Smoke studies were made in the Princeton 4 x 3 foot smoke tunnel to investigate the vortex formation and streamline flow for different dynamic pressure to base pressure ratios. The results showed that the flow behaves very similar to a jet flap in the  $q/p_b$  ratios higher than 1.

#### ALART - Phase III

1. Hampton, P., Effect of Rotor Parameters on the Stability and Control of Unducted Stand-On Helicopters, Princeton Aero. Report No. 462, May 1959.

The study reported herein is a follow-up on the flight test experiments and analysis of an unducted stand-on flying platform. The object was to see whether greatly improved flying qualities could be obtained in a machine of that category with a rotor system of different design. It was initially believed that a flapping rotor of novel hub design would improve the handling qualities by reducing the velocity stability, which was responsible in the original machine for the difficulties of trim in forward flight, gust sensitivity, and dynamic instability.

Flapping rotors with hinge spring restraint and hinge offset were therefore studied analytically to see the effect of those parameters on the stability derivatives of the flying platform. These analytical studies are useful and represent a contribution to general rotor theory aside from the particular application in the report to flying platform vehicles.

With respect to the flying platform, the conclusions may be summarized as follows:

- (1) It would be possible with a flapping rotor incorporating either moderate spring restraint or offset hinges to achieve reasonable flying qualities at airspeeds up to about 40 miles per hour.
- (2) Still further improvements in flying qualities could be achieved with larger spring restraint or hinge offset if auxiliary damping in pitch were provided.

The use of a flapping rotor system probably makes it impractical because of clearance problems to use counter-rotating blades for torque balance and this in turn indicates a need for tip jet propulsion to eliminate the unbalanced torque of the single rotation rotor.

2. Traybar, J. J., Longitudinal Stability and Control of a Ducted Rotor Flying Platform, Princeton Aero. Report No. 464, June 1959.

Analytical studies are performed to predict the flying qualities of a ducted rotor flying platform. The work is related to previous experimental flight tests and analytical studies of an unducted stand-on helicopter wherein certain stability and control deficiencies were noted and explained. It was desired to determine whether similar deficiencies would exist in the ducted rotor design. Rather extensive wind tunnel data were available for a machine of this general type and were used as a basis for the theoretical predictions.

It was determined that the flying qualities of a ducted rotor flying platform at very low speeds and hovering might be made marginally acceptable by a suitable duct design and center of gravity location and auxiliary damping devices. The design parameters for this flight range

would be very unfavorable for higher speeds where the dynamic response would then be very unstable. No very good compromise which would yield acceptable stability over a reasonable speed range appeared to be possible. Even aside from these stability problems, the rather heavily loaded ducted rotor design is characterized by a need to tilt heavily for trim in forward flight and this in itself would probably make it undesirable for flying platform application.

3. Traybar, J. J., Effect of C.G. Position, Duct Area Ratio, and Duct Angle Ratio on the Performance of an Aerial Jeep Type Aircraft, Princeton Aero. Report No. 494, January 1960.

Theoretical studies are presented showing the effects of duct configuration on the performance of a multi-duct aerial jeep-type aircraft. It was determined that only small savings of power can be achieved by optimizing the distribution of duct area front to rear and the ratio between front and rear duct tilt angles in forward flight. The large induced power, for hovering, and the small reduction of it in forward flight are characteristic of the high disc loadings used and they cannot be much improved by optimizing the above parameters. Best distribution of duct area seems to occur with the front duct area about 50% larger than the rear and with front and rear duct rotation for trim about equal. Best center of gravity location is the one where all ducts are equally loaded and hence varies with forward speed. Again, however, compromise with off-optimum location is not very severe.

#### ALART - Phase IV

1. Goldberg, J. H. and Gangwish, R. C., Required Lateral Handling Qualities for Helicopters in Low-speed Instrument Flight, Princeton Aero. Report No. 496, February 1960.

A program of flight tests with several different pilots flying a variable stability helicopter was conducted to determine the effect of certain stability and maneuvering characteristics on the suitability of lateral handling qualities for low-speed instrument flight. In order to keep the time and budget within reasonable bounds, the investigation was restricted to types of handling characteristics generally considered to be favorable and which, for some helicopters, could be obtained only with artificial stability augmentation devices.

The findings apply to low-speed flight on instruments as typified by instrument landing approach using ILS or Zero Reader type indicators. The important factors for these flight conditions were determined to be damping of Dutch Roll oscillation and the divergence of the Spiral Mode. Allowable values of these two parameters are inter-related as indicated by the graphical display of results in the report. The Dutch Roll oscillation should in no case be less damped than would correspond to half amplitude in two cycles. The Spiral divergence should in no case be stronger than would correspond to double amplitude in seven seconds. Spiral convergence is desired although mild divergence is acceptable if Dutch Roll damping is sufficient.

It was further determined that a necessity to maintain noticeable control deflection in steady turns is undesirable. These effects are less important than the stability parameters above, but they are well defined and should be considered as limiting the spiral stability, yaw damping, attitude stabilization, or other stability parameters which affect trim in steady turns.



A number of other parameters were considered to be relevant to the investigation but seemed to be of secondary importance and their effects could not be defined accurately because of the brevity of the program.

2. Miller, George E., An Investigation of an Inertial Velocity Measuring System for Use on a Variable Stability Helicopter, Princeton Aero. Report No. 544, April 1961.

For the investigation of helicopter stability characteristics in hovering, it was necessary to provide an electrical signal proportional to airspeed as an auto-pilot input. This was in the variable stability helicopter, where it was necessary to change the velocity stability derivative. Various methods of sensing airspeed were considered, including Doppler radar and the Cornell Aeronautical Laboratory blade tip system as well as the inertial velocity system finally adopted. The last appeared to offer a useable device with the least development time and cost. Several compromises in design were required, however, by the drift of the controlling gyroscope and the earth's turn rate. The design methods and resulting adjustments of the nonlinear erection system are described in the report and would be valuable to research or design groups with similar problems. The ultimate result was an inertial velocity sensor which could be used to provide an autopilot input proportional to velocity for short periods of time as required for investigations of handling qualities in near-hovering flight.

3. Seckel, E. J., Traybar, J. J., and Miller, G. E., The Effects of Helicopter Stability on Handling Qualities in Steep Descent, Princeton Aero. Report No. 584, December 1961.

It has been found empirically that helicopters are very difficult, if not impossible, to control accurately under instrument flight conditions at very low speeds as would be required for steep instrument approaches to

landing. There appear to be several reasons for this, including large effects of wind and turbulence; unfavorable sensitivities of bank, turn, and altitude control; and unfavorable helicopter stability. A series of tests is in progress, using a variable-stability helicopter and a simulated ILS approach system to determine the degree of improvement in handling qualities that can be effected by changes in the helicopter stability characteristics. It is expected that favorable modifications to velocity and angle of attack stability derivatives will provide better handling. This investigation should be followed by further flight trials to show the effect of airspeed and rate of descent and changes in instrument display. The first phase of the above work is expected to be completed under the ALART Contract.

4. Seckel, E. J., and Traybar, J. J., Longitudinal Handling Qualities Requirements for Precision Hovering in Turbulence, Princeton Aero. Report No. 585, December 1961.

A series of flight tests with a number of qualified pilots and a variable-stability helicopter was conducted to determine the effect of certain stability parameters on the ability to do precision hovering in atmospheric turbulence. The pilots flew the aircraft near the ground around a course with several stops and brief hovers and, at the end, speared and lifted hoops with a probe fastened to the helicopter. The whole course emphasized the handling qualities which would be significant for the precision control required to pick up sling loads, deliver litter patients, dunk Sonar buoys, etc. under gusty conditions.

The effect of velocity stability was determined to be of particular importance. The most important effect is that the disturbances felt by the pilot due to turbulence are essentially proportional to this parameter. Secondary effects are on the control gradient for trim at low forward speeds,

and the dynamic stability. The range of velocity stability variation was from practically zero, which was considered very favorable, to values that were considered by pilots to be unacceptable or even disastrous. Analysis of these data to determine the best presentation of it for incorporation into military specification is in progress at this writing.

It was discovered, in the course of the above investigation, that certain pilot ratings did not correspond to previously published handling qualities criteria. Further investigation disclosed that somewhat higher angular damping and appreciably greater control effectiveness are desired by pilots for the precision hovering than had previously been thought. This finding should certainly be incorporated into military specifications for an aircraft required to perform under the subject conditions.

#### ALART - Phase V

1. Dukes, T. and Gangwish, R., Interim Report on a Flying VTOL Flight Simulator Study, Princeton Aero. Report No. 502, March 1960.
2. Goldberg, J. H., A Flying Flight-Simulator, Princeton Aero. Report No. 455, May 1959.
3. Witt, Howard R., Approach to a Flying Flight Simulator, Princeton Aero. Report No. 461, May 1959.

The above three reports present the results of preliminary design study of the instrumentation required for a flying simulator of VTOL aircraft. The simulator would be required to exhibit all the handling qualities of a VTOL aircraft from hovering and slow rearward flight into forward flight through transition and including slow cruising flight in airplane configuration. The trim and static and dynamic stability characteristics must be accurately represented including the effects of ground proximity and nonlinearities. A novel instrumentation system is devised which would provide

the desired characteristics independent of the simulator helicopter properties. The contemplated design is shown to be stable and feasible with existing components, provided certain design features are provided. The resulting simulator would provide simulation of complete flights of the VTOL aircraft, including take-off and landing, hovering, transition to forward flight, and cruising in airplane configuration. Similarity of translational as well as angular response in small and large motions would be provided over the entire speed range. Even simulation of atmospheric turbulence would be incorporated.

The features and capabilities of the simulator contemplated above are considered to be essential to the further investigation of V/STOL handling qualities. They are certainly required for reasonable simulation of the nonlinearities and rapid changes of stability with airspeed in transition. The latter are the distinguishing features of VTOL aircraft about which very little is known and where appreciable effort will be required before service use can even be contemplated. Most of the above novel features are not available nor even planned for any existing simulator.

#### ALART - Phase VI

1. Durbin, E. and Born, G., A Short Discussion of the Feasibility of the Use of Radioactive and other Coatings in Eliminating Aircraft Electrical Charge, Princeton Aero. Report No. 570, September 1961.

This is a discussion of the feasibility of the use of passive coating methods in reducing the accumulation of charges on an aircraft in flight. The report includes a discussion of the size of radio-active sources required and the radiation hazards therefrom. It also includes the principles of passive coatings and the major problems involved in the use thereof.

2. Durbin, E. and Born, G., Study and Investigation of Various Methods to Control the Charge of a Helicopter, Princeton Aero. Report No. 582, December 1961.

A short theoretical study is pursued of the charging and discharging problems of an aircraft in flight, together with some simple laboratory experiments.

The report deals with the following subjects:

- a) The hazards of a charged aircraft.
- b) The natural charging and discharging processes and the factors which determine the charge of a helicopter in flight.
- c) A study of the feasibility of the possible methods of solution of this problem such as coating, radioactive sources, passive corona points, active DC, AC and/or a combination of AC and DC corona systems.
- d) Discussion, based on above study, of the practical approach and construction of a discharge system.

#### ALART - Phase VII

1. Payne, H. E., A Study of V/STOL Aerodynamic Static Test Facilities, Princeton Aero. Report No. 545, April 1961.

A series of visits to centers of V/STOL industry and research is reported. The objective was to determine the adequacy of the country's facilities for aerodynamic model testing of VTOL aircraft designs. It was determined that there are two wind tunnels in the United States in which it is possible to test models of practical size of aircraft designs characterizing strong slipstreams. These are the full-scale tunnel at Langley Field and the 40 x 80 foot tunnel at Ames Laboratory of the NASA. Other tunnels in the country are too small. Their test sections are too small and the flow conditions in the return passages are unacceptable.

Industry representatives seem to agree that facilities for testing their designs are not in fact available. In some cases, industry representatives even express uncertainty about how such tests should be planned and carried out to provide meaningful aerodynamic data for design purposes. It is shown in the report that tests should be devised preserving geometric similarity between model and full-scale, preserving advance ratio, and flow angles. In addition, the blade (propeller or rotor, 3/4 radius) Reynolds Number should be at least one million and the tip Mach number must not exceed the compressibility limit. These requirements result in a propeller blade chord of about  $2\frac{1}{2}$  inches minimum, which in turn means minimum propeller diameters of roughly two feet. Model size for a typical configuration will be the order of 8 to 10 foot span minimum and for acceptably small wall interference the tunnel test section dimensions should be approximately 40 x 50 feet. Model disc loadings will be approximately the same as full-scale and the range of tunnel speed must be approximately the same as the full-scale speed range under investigation. The latter has been taken to be from zero to 150 knots.

In summary, the aerodynamic test facilities in the United States are unsuited to the V/STOL model testing required, and in addition they are fully occupied with work on other types of aircraft so that they are largely unavailable for such a purpose. The character and specifications of a wind tunnel for V/STOL testing are determined and it is shown that the subject tunnel would be feasible and practical.

#### ALART - Phase VIII

1. Dukes, T. and Hargraves, C., A Study of Artificial Stabilization of Ground Effect Machines, Princeton Aero. Report No. 583, December 1961.

A study of artificial stabilization of ground effect machines is being made during the last half year of the ALART program. The purpose of this study is to investigate the feasibility of stabilizing the GEM by means of feedback methods. In the present state of the art, less sacrifice in performance can be expected from the use of artificial rather than from aerodynamic stabilization.

This report deals with the following subjects:

- a) The development of a simplified mathematical model for the purpose of analytical and computer studies.
- b) The results of tests conducted in order to support certain assumptions made in the mathematical model.
- c) A discussion of the specific problems involved in the feedback control of a ground effect machine.
- d) Preliminary mathematical synthesis of an artificial stability augmentation system.
- e) The results of a computer study of the feedback control system using the mathematical model.
- f) An estimate of the improvement in stability, controllability and handling qualities to be expected.

Because of the extremely wide range of characteristics due to nonlinearities and because of considerable lack of quantitative knowledge, it has been already suggested that this work be continued to study the feasibility of applying the adaptive control principle to similar problems inherent with most low speed flying machines.

#### IV. General Recommendations and Conclusions

Specific technical recommendations for each of the studies of all phases of ALART are made in the respective technical reports.

In the larger sense it is believed that the over-all results have been beneficial and well worth the dedicated efforts of both Army and Princeton personnel, although it has been necessary to negotiate many differences of opinion.

It is hoped that the new and more extensive ALART program envisioned by TRECOM and Princeton will, with a vigorous and sympathetic approach to research, accomplish heretofore unattainable goals.



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Technical Report  
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The Princeton University - U. S. Army ALART program, contract No. DA-177-TC-524, has spanned the time period January 1, 1959 to December 31, 1961 and has been exclusively devoted to research in several areas of low speed flight. The end product of this work is a number of technical reports, each of which is summarized in this paper.

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Princeton University Aero. Eng. Dept., Princeton, N. J.		1. Airplanes, VTOL-Test facilities	Princeton University Aero. Eng. Dept., Princeton, N. J.		1. Airplanes, VTOL-Test facilities
Final Report - A SUMMARY OF THE PRINCETON UNIVERSITY - U. S. ARMY ALART PROGRAM		2. Airplanes, VTOL-Stability	Final Report - A SUMMARY OF THE PRINCETON UNIVERSITY - U. S. ARMY ALART PROGRAM		2. Airplanes, VTOL-Stability
Report No. 566, January, 1962		3. Helicopters-Test facilities	Report No. 566, January, 1962		3. Helicopters-Test facilities
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